RASC FY03 Study Summary
Space Theme 1:
Looking for Life & Resources in the Solar System

March 2004

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Robotic Exploration of Titan
JPL

Mr. Wayne Zimmerman - PI, Titan Surface & Sub-Surface In-Situ System

Dr. Marco Quadrelli - PI, Sonde "Herd" Fleet Control

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Team: JPL, CalTech, University of Arizona

Dr. Ram Manvi - JPL RASC Task Integration

Dr. Charles Weisbin - JPL RASC Program Manager

LaRC & GRC Support

Titan Study Team Organization

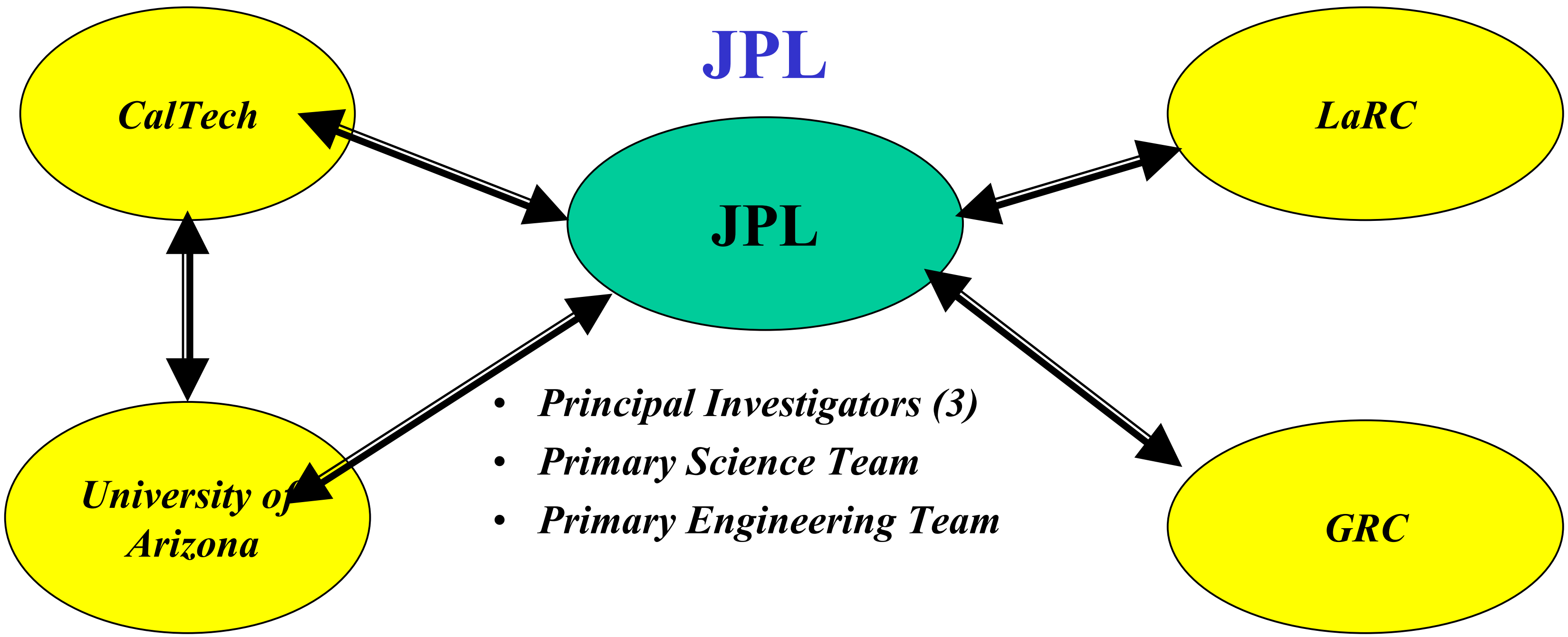
LaRC

- *RASC Integration*
- *Visualization Animations*
- *Technical Support:*
  - *Aeroentry/Aeroshell*
  - *Far-Term Communications*

CalTech

➢ *Titan Chemistry*

JPL



- *Principal Investigators (3)*
- *Primary Science Team*
- *Primary Engineering Team*

➢ *Titan Science/Cassini Mission Background*

Univ of AZ

- *Technical Support:*
  - *Far-Term Transportation*

GRC

Titan Study Tasks

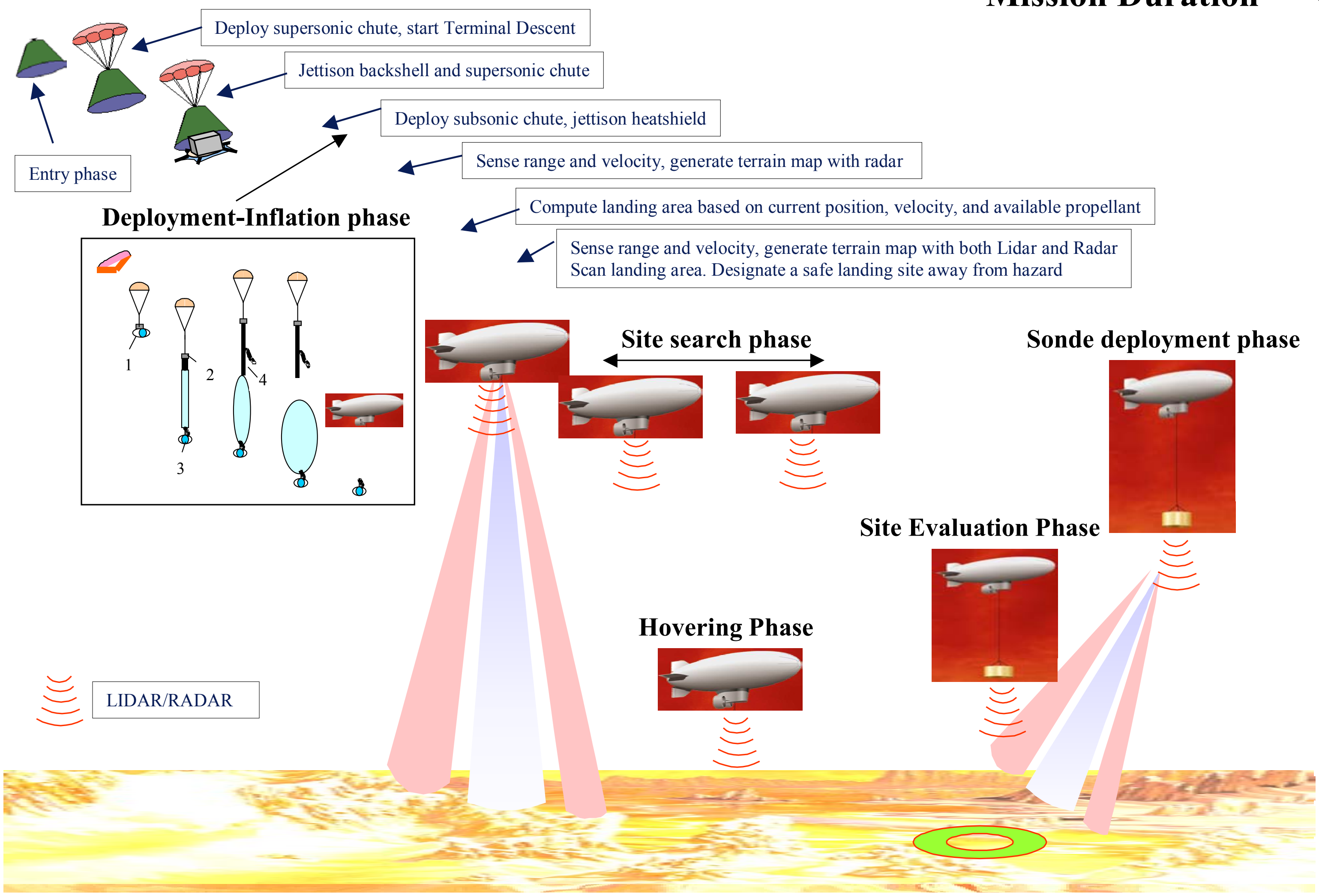
- ***Define science objectives, instruments, & system requirements***
- ***Develop a science-driven mission concept, focusing on:***
  - *Robotic search for biomarkers & pre-biotic chemistry*
  - *Sample collection & geologic mapping of Titan's surface*
- ***Identify mission concept architecture elements***
- ***Create a concept for autonomous, in-situ mobile "robotic sensors" to explore Titan's surface & sub-surface using:***
  - *A "herd" of sondes with sample collection "harpoons"*
  - *An aerial platform for "herd" transportation & deployment*
- ***Develop "herd" guidance, communications, & control concepts***
- ***Develop hardware & software survivability methods***
- ***Perform supporting trades & analyses***
- ***Develop selected system design concepts***
- ***Identify enabling technologies & technology challenges***

Science Objectives

- **Determine Titan's pre-biotic & proto-biotic chemistry.**
  - *Determine if complex organics exist involving C, H, O, N*
  - *Determine if self-organizing chemistry occurs or has occurred on Titan*
  - *Measure the ^{13}C, N, and O surface abundances & distribution*
- **Understand Titan's surface organics (distribution, composition, organic & chemical processes and context, energy sources).**
  - *Examine the chemistry taking place on the surface & near-surface of Titan*
  - *Identify the composition of organics on Titan's surface*
  - *Determine what organic chemical processes are occurring on Titan*
- **Identify geological & geophysical processes relating to Titan's evolution**
- **Explore Titan's atmospheric dynamics, meteorology, & surface interactions**
- **Understand Titan's atmospheric chemistry**
- **Explore the nature of Titan's upper atmosphere & its interaction with the magnetosphere & solar wind**
- **Determine Titan's formation & the implications for Saturn's formation**

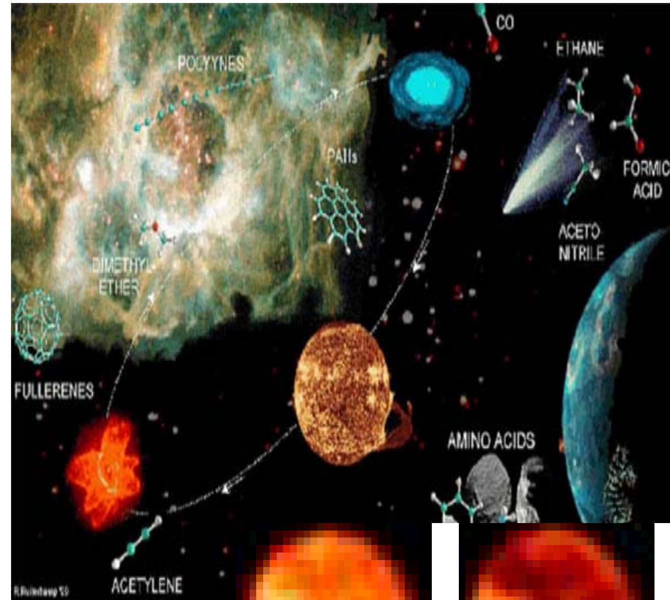
TITAN MISSION CONCEPT

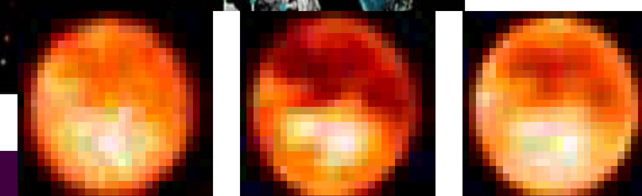
Mission Duration = ~40 days

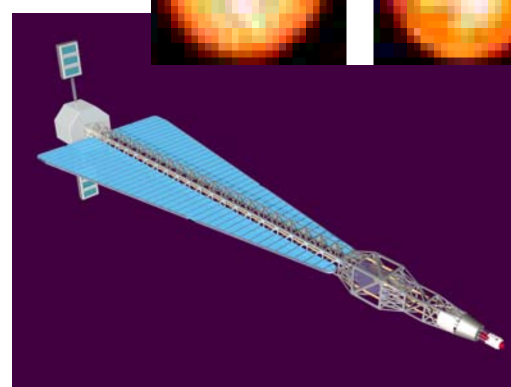


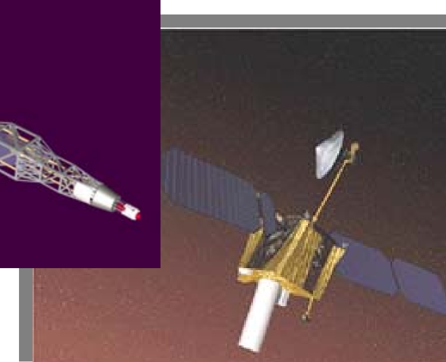
Primary Trades & Analyses

- **Mission Transportation Architecture**
  - *Near-Term Mission Concept "Baseline": Launch 2010, 6-yr cruise*
  - *Far-Term Mission Concept: Launch 2020, ~11-year cruise*
- **Mission Science**
  - *Instrument Suite (incl. mass & volume)*
  - *Instrument Delivery & Deployment*
  - *Robotic Sondes: Mobile, Tethered*
  - *Sample Acquisition & Extraction*
- **Supporting Studies**
  - *Sonde Herd Control Methods*
  - *Hardware & Software Survivability*
- **Communications**
  - *DTE feasibility in Near-Term Mission Concept*
  - *Dedicated Orbiter; Aerial Platform; Sonde Herd in Far-Term Mission Concept*
- **Supporting Trades & Analyses, e.g.**
  - *Trajectory / Orbital / EDL / Aerocapture*
  - *Aeroshell design & packaging*
  - *Technology "Tall Poles"*









Transportation Analyses

- **Getting to Titan: Launch/Cruise Options**
  - *Delta IV-H, Atlas V*
  - *SEP, NEP, Chem*
  - *Venus Gravity Assist (VGA)*
- **Getting to Titan's Surface: Entry Options**
  - *Chemical / Aerocapture*
  - *Aeroshell / Drogue Chute*
  - *Direct ballistic entry*

- ***NEAR-TERM MISSION (2010-2015)*** ***Launch: ~12/2010 or 2011 Titan Arrival: ~12/2016 or 2017***
  - *Mission Scenarios: (1) Integrated Orbiter & Aerial Platform (2) Separate Orbiter & Aerial Platform (3) Aerial Platform only (no Orbiter for comm)*
  - *Developed Baseline & Backup concepts for 3 Mission Scenarios; (Example Mission Trade Space), e.g.*
    - *Atlas V, SEP-VGA, 6/7-year transfer + A/C*
    - *Orbiter to 1700 km circular polar orbit, Aerial Platform to atmosphere/surface*
    - *Payload = ~100 kg to Titan surface*

- ***FAR-TERM MISSION (2020-2025)*** ***Leave Earth: 8/14/2017 At Saturn: 6/7/2028 At Titan: 9/29/2028***
  - *All-NEP stage operating at 100 kWe + ion thruster (I_{sp}=6100 sec) + Delta IV-H & + A/C*
  - *Total flight time = 11.33 yrs (2x baseline Chem+SEP+Chem/A/C mission architecture)*
  - *1700 km circular orbit at Titan* *Delivered Payload = 2600 kg*

- ***CONCLUSIONS***
  - *All-NEP concept cannot perform mission in the 5-6 years desired by the science community*
  - *All-NEP stage has more performance for given IMLEO than traditional impulsive at cost of trip time*
  - *Baseline NEP mission, 2600 kg payload delivered, is unclosed*
  - *NEP wet mass stage exceeds single Delta IV H delivery capability to 1000 km*
  - *Limited availability of Xe impacts thruster efficiency*
  - *Venus and/or Jupiter swing-bys may lower total trip time*

Instrument Delivery & Deployment Mechanism(s)

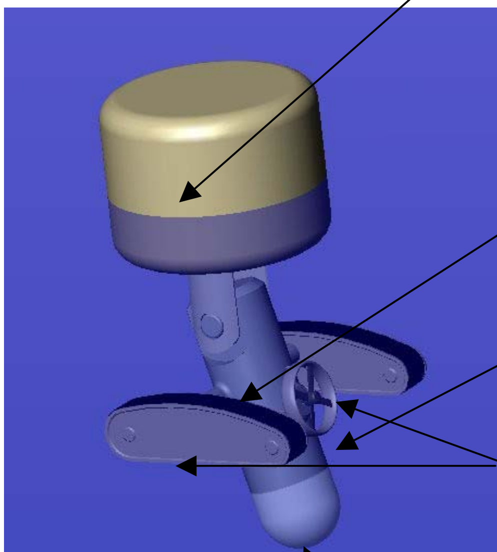
- **Science Requirement**
  - *Sample atmosphere, liquid, & solids over multiple regions*
  - *Best Option: Amphibious sonde (free swimming, crawling, tethered) deployed from aerial platform*
  - *~30 - 35 kg based on current "cryobot system" experience*

- **Surface Instrument Delivery Options**
  - *Aerial Platform performs aerial survey, selects prime science target, deploys three separate sondes*
    - *Tethered, samples atmosphere column*
    - *Free-swimming, samples subsurface liquid column*
    - *Crawler, samples crater rim solids*
  - *Aerial Platform carries one tethered deployable sonde*
    - *Samples atmospheric column, subsurface liquid, crater rim solid*
    - *Aerial Platform provides survey, target selection, sonde deployment, & transportation*

Sonde Instrument Design Concept

- Must operate in liquid / solid surface environments
- Must be able to acquire gas / liquid / solid samples

Sonde upper chamber (tether/actuator, quad dipole patch array/comm avionics, & buoyancy control chambers/ pumps

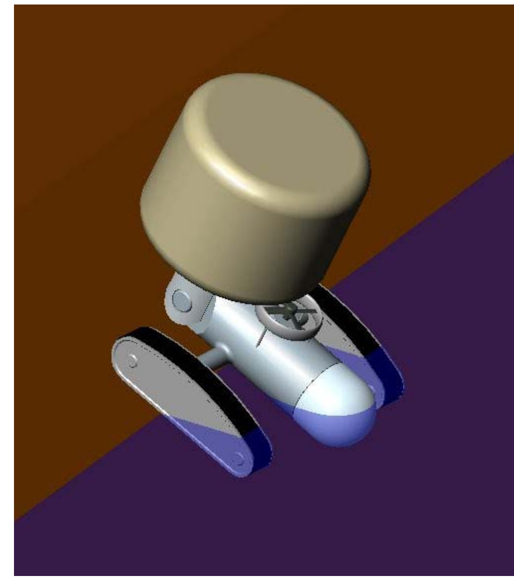


Lower sonde (science inst's/sonde control avionics/power module (RTG/thin film batteries) & SPME/solenoid driven actuators)

Planar thruster

Lifting surfaces (descent/rise control, crawler tracks allow transfer from lake onto crater rim)

RTG (ballast, heat, power)



<u>Current Design Specs</u>

- Upper chamber: 35cm dia x 30cm long
- Lower assembly: 15cm dia x 60cm long
- Lifting surfaces: 30cm long, 10cm wide
- Projected mass: 33kg

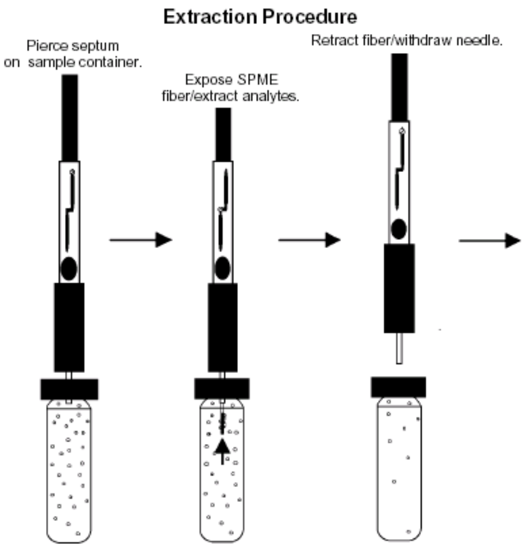
Sample Extraction & Analysis

Requirements:

- Objective: Create conceptual design of sample extraction & handling system
- Take samples from solid ground, liquid lakes, lake bottoms
- Sample size: 5-10 mg
- Penetration depth ~ 5 cm
- Number of samples: 20 liquid & 20 solid

Device Summary

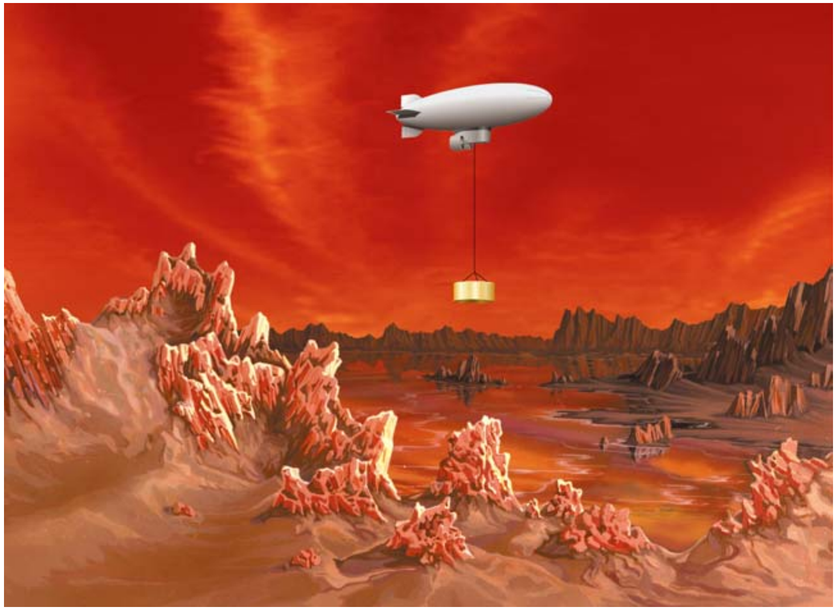
- Liquid sample mass ~15 g total
  - Simple hollow design with holes collects liquid & loose surface solid particulates
  - Liquid sample (~0.2 g) placed into containment vessel for analysis
- Solid sample mass ~ 200 g
  - Helium Propulsion: 0.4 g He provides > 100 m/second harpoon impact
  - Solid Sample Size: 4 cm x 0.3 cm diameter (0.25 g water ice)
  - Liquid Deployment: < 1m recoil
  - Atmospheric Deployment: < 5m recoil



Solid Phase Micro-Extraction (SPME)

Internal length of polymer-coated silica fiber is moved in & out of needle with plunger. The Fiber is exposed to sample, analytes adsorb to polymer coating. Fiber introduced into heated inlet of GC, analytes desorb from coating & enter GC column for analysis. Factors affecting analyte type adsorbed to fiber include thickness of polymer coating & chemical make-up. Extraction times ~ 5-15 minutes.

Sonde "Herd" Control Study



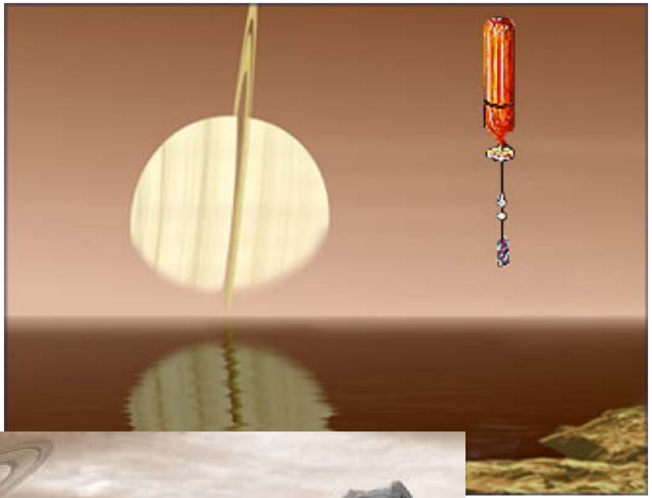
Problem
- Multiple robots offer excellent opportunity for distributed scientific data collection

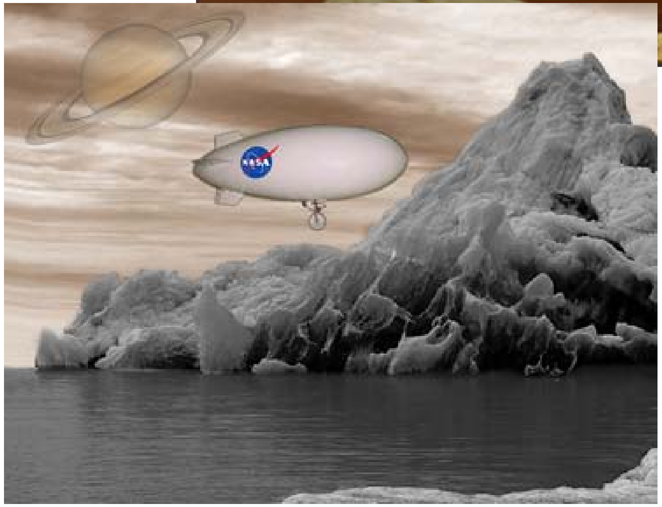
Objective
- Demonstrate active cooperative control of herds of TBD mobile sondes in Titan environment

Approach
- Create algorithms/techniques for cooperative, distributed sensing & control of multiple sondes in Titan's environment
- Demonstrate in simulation

Developed
- Algorithms/techniques for cooperative, distributed sensing & control of multiple sondes in Titan's environment
- Simulation demonstrating concepts

Long-Term Survivability Study





- Developed
  - Conceptual architectures for science, computation & control, communications, mission elements & avionics
  - Component failure models
- Identified "survivability" mechanisms
  - Against low temperature
  - Against other environmental factors (e.g., corrosion)
  - Against hardware / software failure
    - Fault Management
    - Autonomous Fault Diagnosis
    - Distributed Fault recovery & reconfiguration

- **Developed survivable system architecture concept, including fault tolerance, autonomous diagnosis & reconfiguration with evaluation methods & verification**

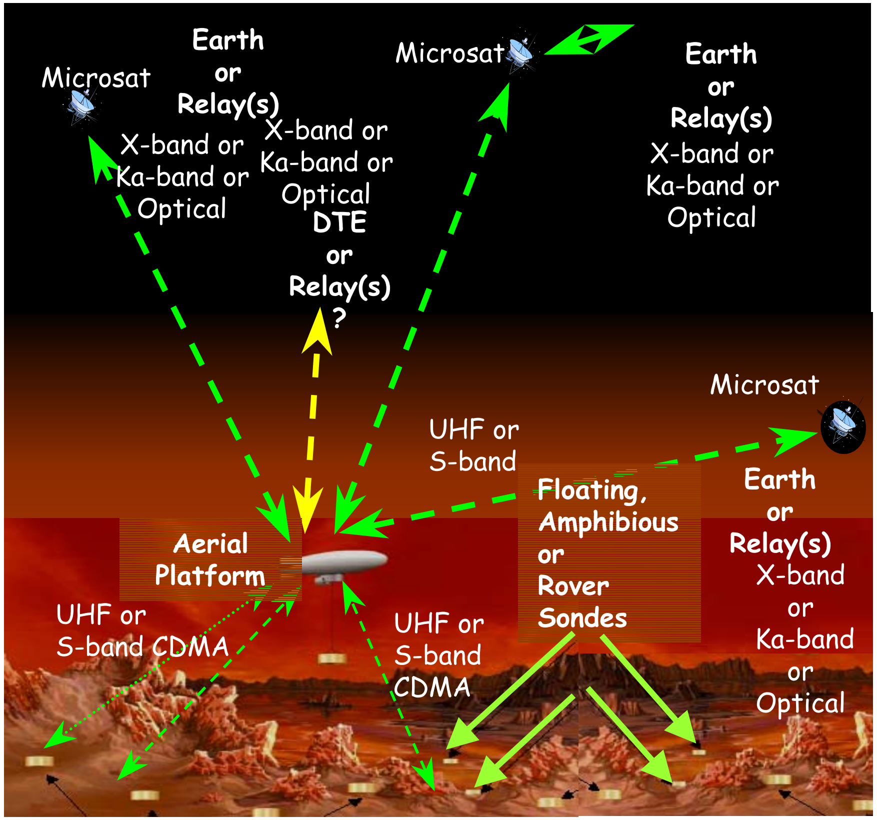
Communications Analysis

(Architecture)

Near-Term Mission Concept Approach: Direct-to-Earth (DTE) link

- **Requires ~ 22 W transmitted power with 35 cm patch arrays**
- **Latitudes > 80° = max coverage**
- **Max DTE link availability = 8 hours/day**
- **Max data volume/day = ~ 3.6 Mbytes/day**
- **Proposed aerial platform antenna: Multiple, non-steerable patch arrays (~ 0.75 kg each) on platform surface or outside gondola with electronic switching between patches**
- **6 patches around platform or gondola, tilted ~ 20° elevation ➔ DTE link with station keeping ~ +/- 3.5 degs over 60 deg interval = ~ 5 kg mass**

Far-Term Mission Concept Approach: Comm Orbiter



- **Dedicated communications & navigation orbiter(s)**
- **May be microsats (~3)**
- **Concept includes inter-element communications:**
  - **Sondes, Aerial Platform, Orbiting MicroSat Relay(s)**

Titan Mission Enabling Technologies*

2.1 Self-Sufficient Space Systems / 4.5 Software, Computing, & Intelligence

- Autonomous control/fault tolerant-redundant S/W architectures
- Systems that can tolerate & intelligently accommodate component failures in Titan environment
- "Failure physics" models & failure modes at ≤ 90° K temperature
- Distributed autonomous failure detection, isolation, & recovery algorithms
- Evaluation of fault management scheme(s) & verification
- Multiple cooperative sonde herd C^3 algorithms

2.7 In-Space Instruments & Sensors / 4.4 Electronics & Sensors / 4.9 Biological Research

- Extremely high-resolution micro-wet chemistry instruments
- Miniaturized in-situ chemical analysis
- Solid Phase Micro-Extraction sample acquisition & control devices
- Solids/residue purging technologies for instruments
- Icy organic sample acquisition & transfer via controlled adsorption/desorption
- Structural/electronics packaging for extremely tight volumes
- Passive/amphibious mobile sondes for organic lake/crater rim sampling
- Micro-harpoon impactors for dense icy materials
- Bio-load reduction & verification for planetary protection

*Using the ASTRA WBS/J. Mankins

Titan Mission Enabling Technologies

2.8 Information & Communications
- GN&C within Titan's atmosphere without communications orbiter
- Steerable phased patch array DTE communications using MEMS/nano-devices

3.6 Lunar/Planetary Exploration Demos
- Aerocapture & aeroentry using ballute or aeroshell
- Balloon mobility system
- Blimp shock alleviation mechanism & dynamic stability during inflation

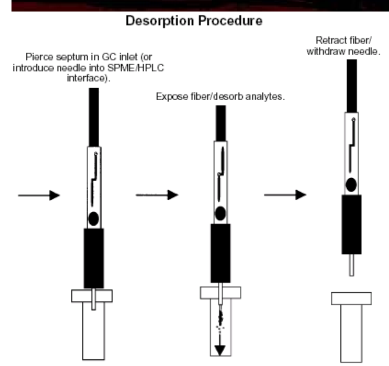
4.1 Advanced Materials
- Ultra-light weight aerocapture/aeroshell materials
- High efficiency NEP/high-yield radioisotope materials
- Cryogenic balloon materials, packaging for cryogenic deployment, actuators/valves/seals, cryo-tether materials
- Titan surface/atmosphere "simulants" for testing & validation

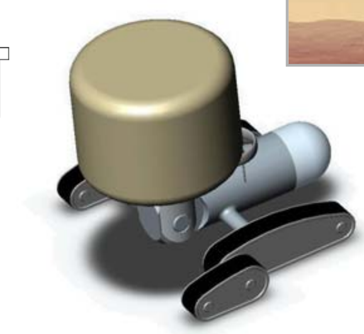
4.3 Power/Thermal/Chemical Technology
- High efficiency SEP cell technology
- Extreme cold sensors/electronics/batteries
- Advanced low-mass radioisotope power system (operable in Titan's atmosphere)

4.7 Advanced Propulsion
- Subsurface mobility propulsive mechanisms for dense cryo-organic liquids

Summary

- Created a science-driven Titan mission concept
- Explored near-term & far-term launch capabilities
- Performed orbit insertion, surface delivery, & aeroshell packaging analyses
- Developed:
  - Sonde & harpoon atmosphere/surface /subsurface sampling concepts
  - Functional control architecture for surface system
  - Sonde & aerial platform design concepts
  - Aerial platform/sonde interface design
  - Thermal control concepts
  - A novel paradigm for cooperative herd behavior in unknown environment
  - Component failure models
  - Survivable system architecture concept
  - A method to provide DTE comm





BACKUPS

Titan Project Team

JPL

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E. Satorius/E. Archer – Communications
J. Jones/J. Hall/B. Dudik – Aerial platform
C. Bergh/W. Fang/W. Zimmerman/E. Kulczycki – Sonde
G. Woodward – Probe deployment/animation
Sengupta – Survivable systems
J. Chang – S/W control architecture
P. Shakkottai/R. Manvi – Thermal systems engineering

LaRC

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Visualization Animations: Rob Kline/Josh Sams

Technical Support
Fred Stillwagen/Jennifer Parker/ Robert Stephens - Comm/Nav
Shawn Krizan/Eric Dyke/ Alicia Cianciolo - Aeroentry/Aeroshell

GRC

Technical Support: Far-Term Transportation
Dr. Stan Borowski/Melissa McGuire

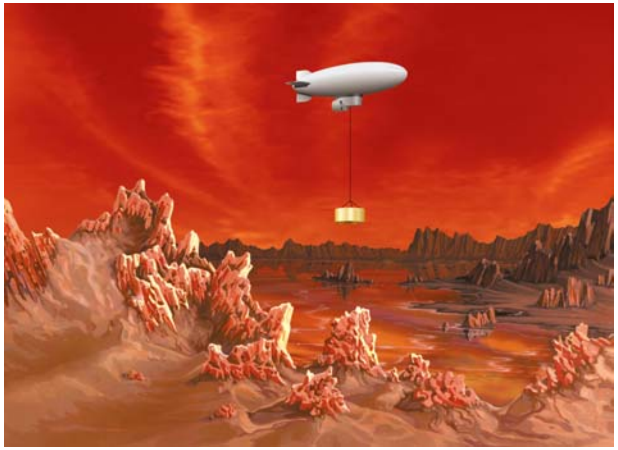
Back

Titan Science -- Background

•	Surface Pressure	1.5 Atmospheres
•	Atmosphere	Primarily N_2 (like Earth), dense, suspended organics
•	Temperature	Low gravity, inverted atmosphere temperature (i.e., surface – 50 km = 70-90K, above 75 km = >115K)
•	Solar flux	1/1000 that of Earth, photochemistry over long time

- **Therefore:**
  - Titan's atmosphere has a huge array of organic compounds & derivatives
  - It "rains organics," forming shallow lakes of organic-rich liquid – similar to the "organic soup" in which, it is generally believed, life formed on Earth
  - Minerals & carbon materials may exist near crater lake rims -- representing ancient origins of early Titan or interior material brought to the surface
- **Primary Mission Science Drivers**
  - *Key Science Driver: Mobility for multiple surface site sampling*
  - *Variety of surface conditions (gas, liquid, ice)*
  - *Balance of surface & atmosphere observations*

Titan Mission Concept



Features

- Aerocapture & entry using aeroshell
- Aerobot mobility system with full control
- Advanced low-mass radioisotope power systems
- Navigation in Titan's atmosphere
- Miniature in situ chemical analysis instruments

System Building Blocks

- Orbiter
  - Provides communication relay
- Aerial Platform / Blimp
  - Science experiments on platform, atmosphere samples, & high altitude mapping
  - Mobility support
    - if non-mobile (drop) sondes or harpoon-type sample collection mechanism used
    - if mobile sondes used under centralized supervision
  - Controls retractable sondes
  - Direct communication and/or relay to Earth (with no Orbiter)
- Sondes (with harpoon-like sample collection device)
  - Reused at multiple geographical sites, tethered
  - Autonomous mobility for amphibious sondes; integrated science experiments for subsurface/surface exploration
  - Science data communicated through tether/patch array relay

Propulsion Options and High-Level Mission Architecture Tradeoffs

Trade	Earth Escape	Escape Prop. TRL	L/V Size	Titan Capture	Capture Prop. TRL	Net Payload	Trip Time
All-Chem	High C3	High	Big	Chem	High	Small	Long
Chem+A/C	High C3	High	Big	A/C	Low	Medium	Long
SEP+Chem	LEO	Moderate	Big	Chem	High	Medium	Medium
	Medium C3	Moderate	Big	Chem	High	Medium	Medium
SEP + A/C*1	LEO	Moderate	Moderate	A/C	Low	High	Short
	Medium C3	Moderate	Small	A/C	Low	High	Very Short
	Aerocapture very efficient at burning off high Saturn/Titan orbit capture/insertion ΔV resulting from high cruise velocity needed for short trip times						
NEP*2	HEO	Low	Big	NEP	Low	High	Medium
	NEP provides 100s of kWe at Titan. Can enable radar mapping of surface (sub-surface?) from orbit, real-time data relay return, etc.						

*1: Selected for Near-Term Mission Concept
*2: Selected for Far-Term Mission Concept

Example Overall Mission Trade Space (Chem+SEP+VGA)

Launch Vehicle	Delta 4450				Delta IV Heavy									
Gravity Assist	VVVGA	VGA	EGA		VVVGA		VEEGA	VEEGA	VGA		EGA			
Earth to Saturn Prop System	Chem	SEP	Chem	SEP	Chem		Chem	Chem	SEP		Chem		SEP	
Titan Capture	Aero	Aero	Aero	Aero	Chem	Aero	Chem	Chem	Chem	Aero	Chem	Aero	Chem	Aero
				7										
Cruise Time to Titan (yrs)	9.3	5.7	7.5	5.9	~11.3	9.3	9.9	~11.9	~7.7	5.7	~9.1	7.1	~8.1	6.1
Launch C3 (km2/sec2)	9.7	10.2	28	8.6	9.7	9.7	12.1	12.1	36.2	36.2	47.7	47.7	17.8	17.8
SEP Power (kW)	---	24	---	24	---	---	---	---	24	24	---	---	24	24
Entry Velocity (km/s)	6.2	6.5	5.3	6.5	6.2	6.2	5.9	5.9	6.5	6.5	6.6	6.6	6.5	6.5
Earth to Saturn Cruise dV (km/s)	1.35	8.3	1.49	6.7	1.35	1.35	0.2	0.2	6.9	6.9	0.5	0.5	4.6	4.6
Titan Insertion Chem dV (km/s)	0	0	0	0	3.5	0	5.5	3.5	3.5	0	3.5	0	3.5	0
			3		5			5	5,6		5		5,6	
Launch Capability	3339	3298	2250	3423	7106	7106	6759	6759	4135	4135	3141	3141	6019	6019
Propellant Mass[1]	1239	619	892	506	5723	2669	5678	4727	2136	715	2088	489	3500	633
LV to Prop Module Adapter	78	78	78	78	78	78	78	78	78	78	78	78	78	78
Prop Module Dry Mass	424	820	389	810	872	567	868	772	1270	828	509	349	1407	821
Available Payload Mass to Saturn	1599	1781	891	2029	433	3792	135	1182	651	2514	466	2225	1033	4488
Prop Mod to Payload Adapter	61	61	61	61	61	61	61	61	61	61	61	61	61	61
Direct Entry Payload Mass	364	364	364	364	364	364	364	364	364	364	364	364	364	364
Payload in Titan Orbit	511	511	511	511	573	511	573	573	573	511	573	511	573	511
Aerocapture System[2,4]	515	515	515	515		515				515		515		515
Pre-Insertion Ejected Mass	133	133	133	133	73	133	125	73	73	133	73	133	73	133
Required Mass To Saturn	1584	1584	1584	1584	1071	1584	1123	1071	1071	1584	1071	1584	1071	1584
Payload Surplus (Deficit) Mass	15	197	(693)	445	(638)	2208	(988)	111	(420)	930	(605)	641	(38)	2904
System Mass Margin				29.8%	(LV - CBE) / LV									
System Reserve				13%	(LV - Growth) / LV									

Assumptions and Notes:

All masses are growth mass listed in kg

[1] Propellant mass calculated using "Launch Capability" as system total mass; Isp = 325, includes 10% mass contingency

[2] Aerocapture mass for Chemical Earth to Titan Prop Modules may change slightly (entry velocity not equal to 6.5 km/s)

[3] This launch capability is extrapolated data

[4] Aerocapture mass includes propellant for circularization delta-V

[5] Assumes delta V required for capture can be reduced from ~5.5 km/s to 3.5 km/s through Saturn/moon tour. 3.5 km/s is estimated, no supporting analysis

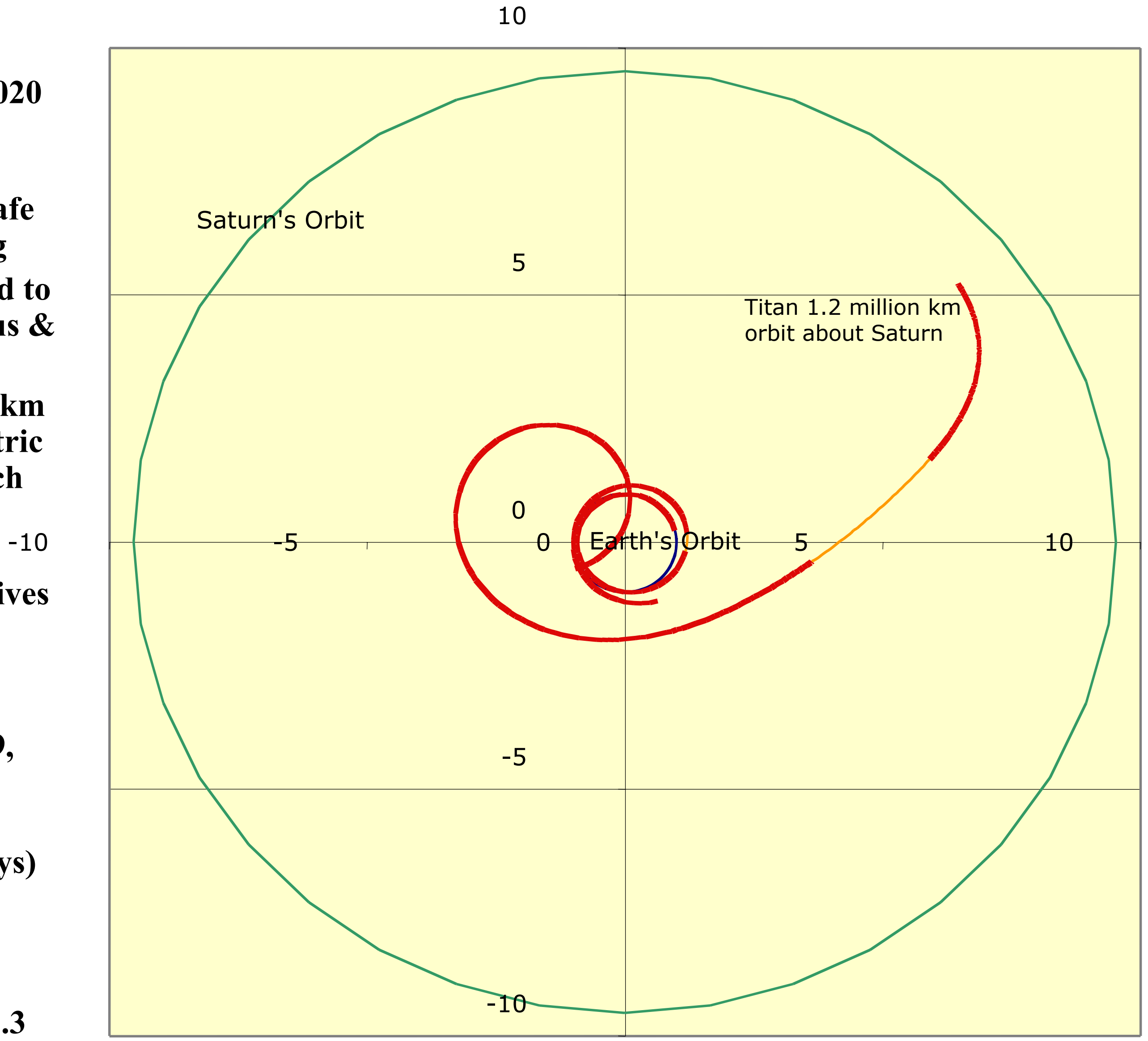
[6] Propellant mass and Prop Module Dry Mass for SEP / Chem options includes propellant and dry mass for both SEP and chemical stages

[7] Titan Aerocapture Study Reference Mission

All-NEP 2020 Mission Concept

Assumptions & Results

- Assume Project Prometheus Nuclear In-Space propulsion 2020 Launch direct to Titan
- 100 kWe NEP transfer stage delivered to 1000 km nuclear safe orbit by Delta IV H (~21,600 kg
- Titan 2600 kg payload delivered to 1000 km by ELV for rendezvous & dock
- Spiral escape from Earth 1000 km circular LEO to enter heliocentric space begins Aug 14, 2017, reach heliocentric space Oct 7, 2019
- Spiral capture/slow down into Saturn sphere of influence, arrives June 7, 2028
- Low-thrust spiral capture into Titan 1700 km circular orbit; complete spiral capture Sept 29, 2028
- No optimizations performed to reduce trip times (e.g., swing-bys)
- Assumed baseline payload delivered ~2600 kg to 1700 km circular orbit about Titan
- Total Trip Time: 4134 days (11.3 years)



Back

Science Measurements, Sampling, & Instrumentation

Primary sampling goals are:

- Sample Titan’s atmosphere near the surface
- Sample organic-rich lakes (both surface & subsurface bottom material)
- Sample the solid organic rich ice at the rims of the cratered lakes

Science Measurements:

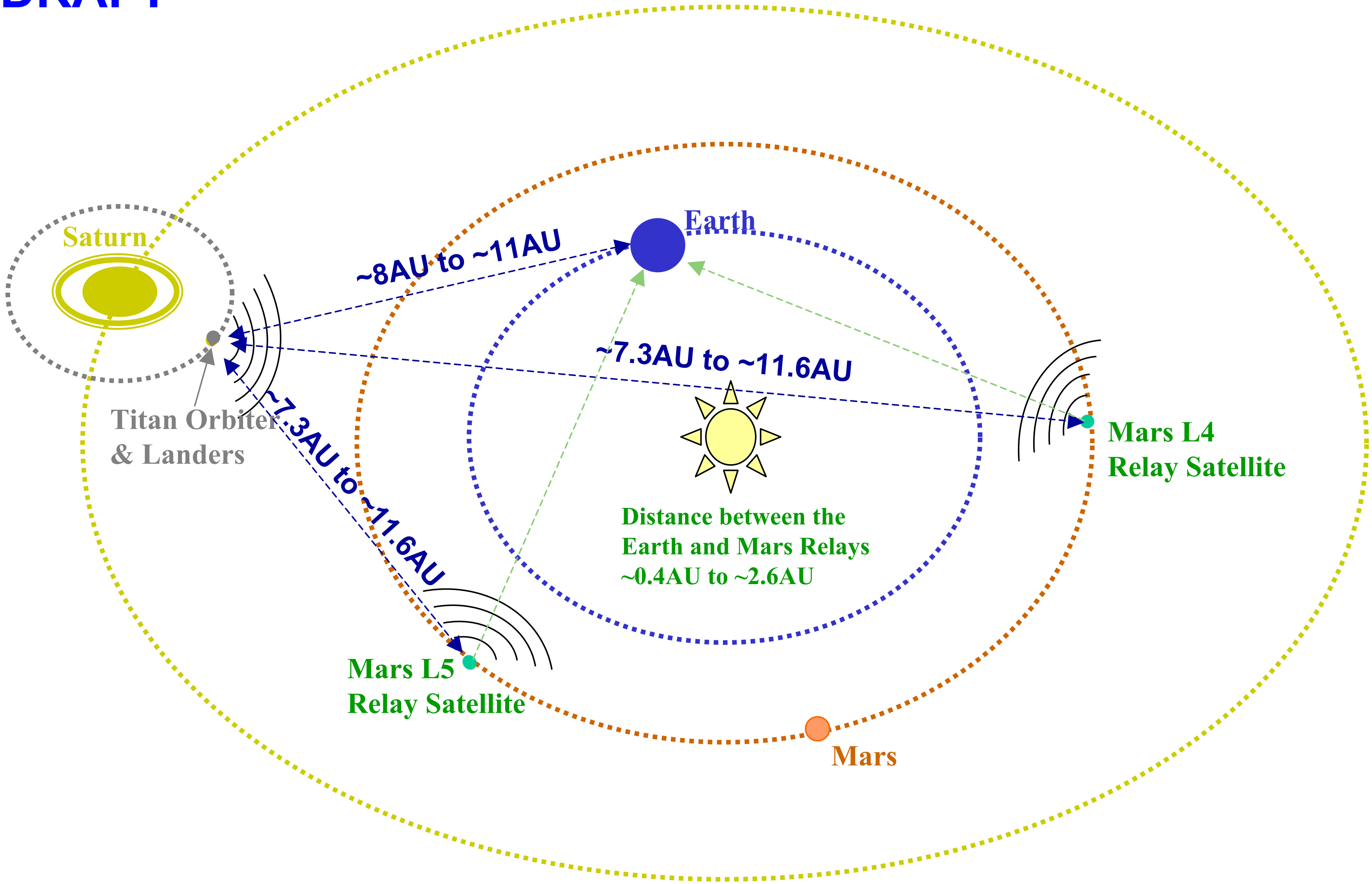
- Perform complete gas/liquid/solid analysis of constituents
  - Examine make-up of tholins & evaluate for presence of chirality
- Perform complete physical study of subsurface liquid column in shallow crater lake
  - Sample column as well as bottom material
- Perform shallow subsurface (<10cm depth) analysis of crater rim(s) solid icy conglomerate material bordering shallow lakes
- Measure: Temperature, Pressure, Liquid Density (via Acoustic Ranging), Conductivity/ Dielectric, LED-Turbidity

Potential Instrumentation

- Microscopic/near field imager
- Gas Chromatograph / Mass Spectrometer (measures organic signatures, detects chirality)
- UV fluorescence (detects specific amino acids)
- Nuclear Magnetic Resonance Spectrometer (detects organic polymers with high resolution)
- Piezo-electric Chemical Detector (detects specific polymers)

Titan Mission
Preliminary Communications Architecture

DRAFT



Miniature Gas Chromatograph (GC) / Mass Spectrometer (MS) Review & Analysis:

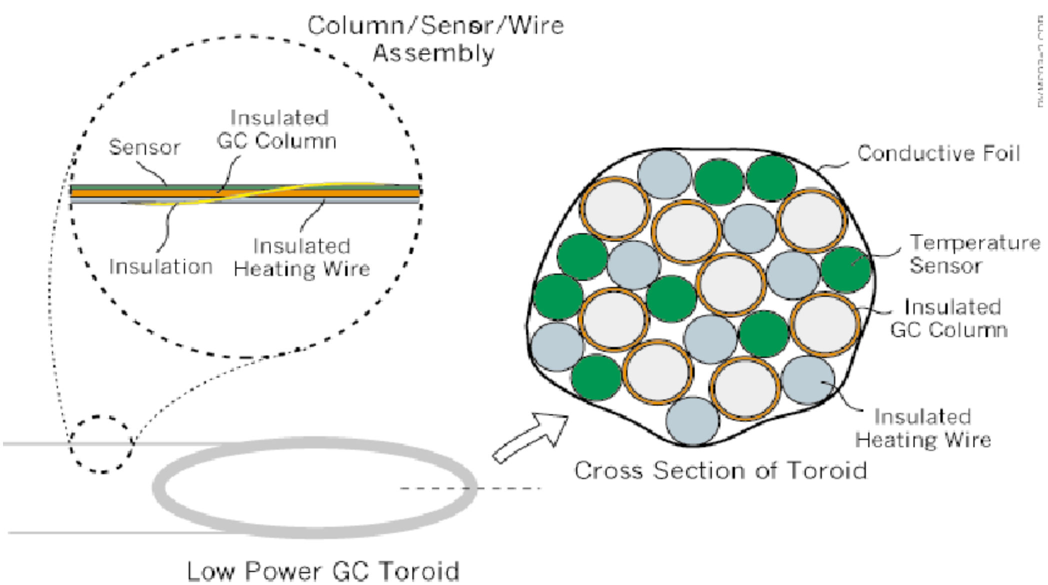
What are Our Best Near-Term / Far-Term Instrument Options for Studying Titan Tholins / Chirality

- Miniature GC Overview
- Miniature MS Overview
- Combined Instruments
- Recommendations
  - o 2010 Mission
  - o 2020 Mission

Miniature Gas Chromatographs

Nanotek, Inc. GC column with thermoelectric heating

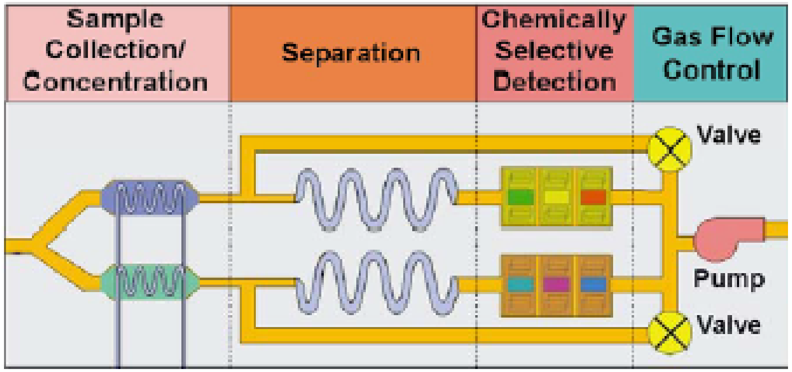
- **40x40x12.5 mm, 77 g**
- **60W peak power**
- **4 m column length**

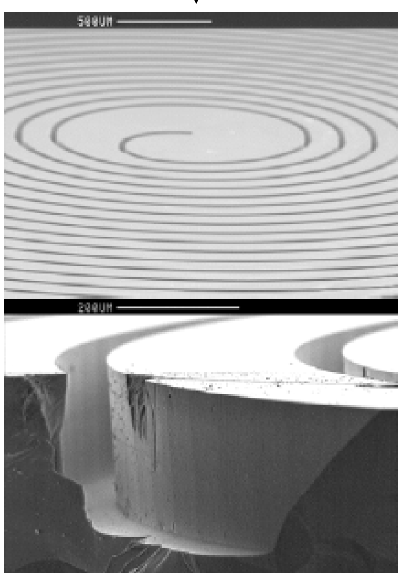


U. Mich.

- **Column/heater assembly**
- **~1 W consumption**

Miniature Gas Chromatographs -- Micromachined Instruments



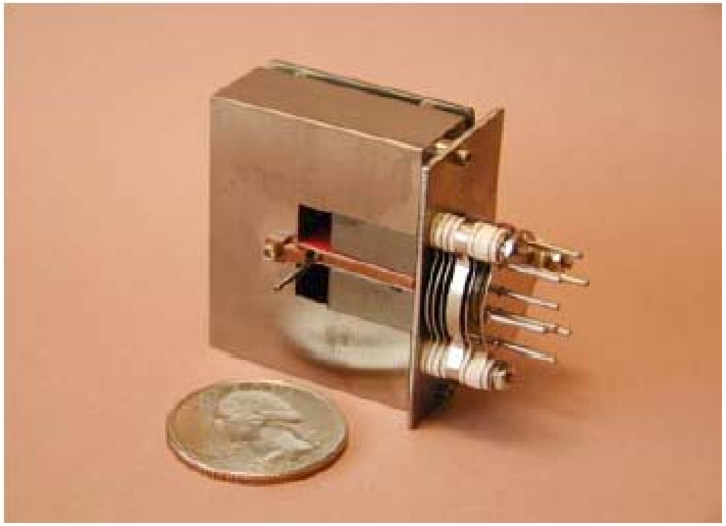


Sandia μChemLab

- 1 m column micromachined on Si
- Polymer coated SAW array detector
- ~1000 cm^3 complete system

LLNL has developed a similar system based on a 5m Si micromachined column with TCD detector

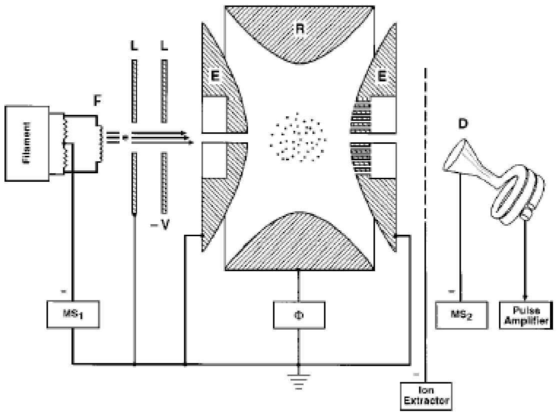
Miniature Mass Spectrometers -- Sectors



Mass Sensors, Inc.
E×B Spectrometer
- 220g, 294 cm^3, 3 W spectrometer
- 2.7 kg, 6555 cm^3, 10 W electronics

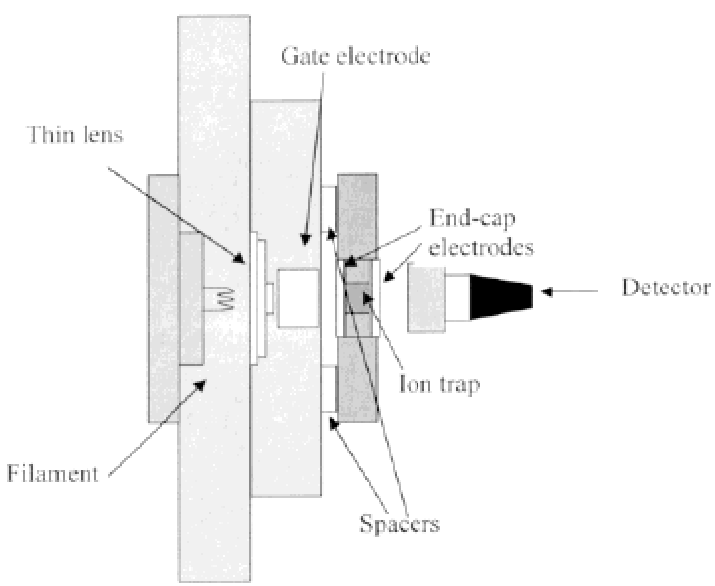
M.P. Sinha (JPL) Mattauch-Herzog sector
- <10kg
- 5.1 cm focal plane

Miniature Mass Spectrometers -- Traps



A. Chutjian (JPL) Paul trap

- **4-6 W trap**
- **"Compact"**
- **m/Δm=380 (baseline isotopic)**

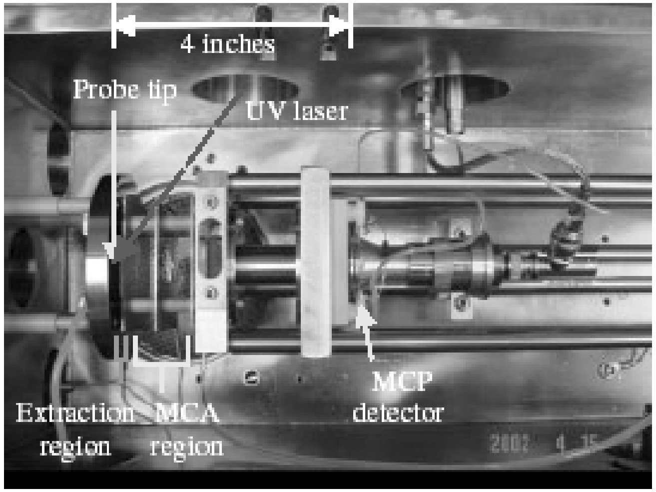


R.G. Cooks (Purdue) cylindrical trap

- **200-300 W complete (50-60% computer), 0.19 m^3, 55 kg**
- **m/Δm = 100**
- **MS^n**

Miniature Mass Spectrometers -- TOF

Ionwerks, Inc. CompactTOF
- m/Δm = 800
- Variety of ion sources



Robert Cotter, Johns Hopkins
- 4-inch MALDI-TOF

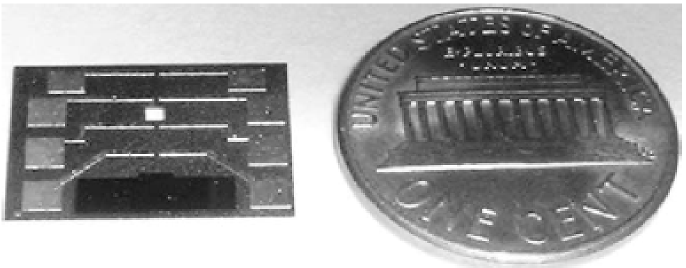
Miniature Mass Spectrometers -- RGAs

Ferran Scientific, Inc.

Symphony Residual Gas Analyzer

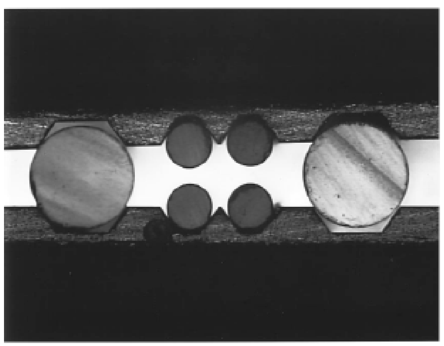
- **2 mm quad array**
- **300 g with electronics**

Miniature Mass Spectrometers -- Micromachined Instruments



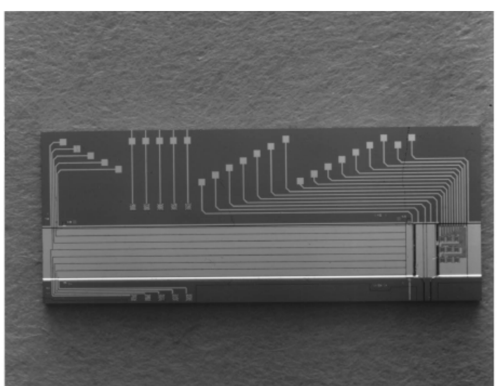
H.J.Yoon(Ajou University, S.Korea) microTOF

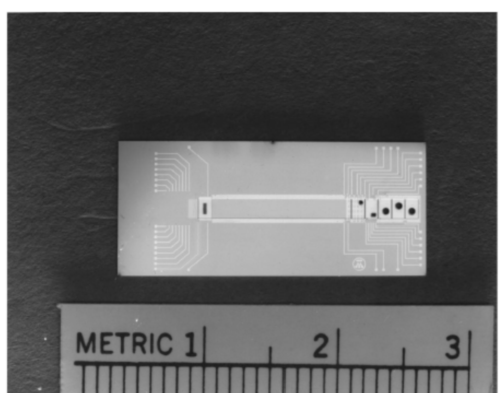
- Micromachined on Si
- 0.1 cm^3 ion source and separator
  - no integrated detector



Tunstall (Liverpool University) Quad

- 500 μm diameter metalized glass rods on Si





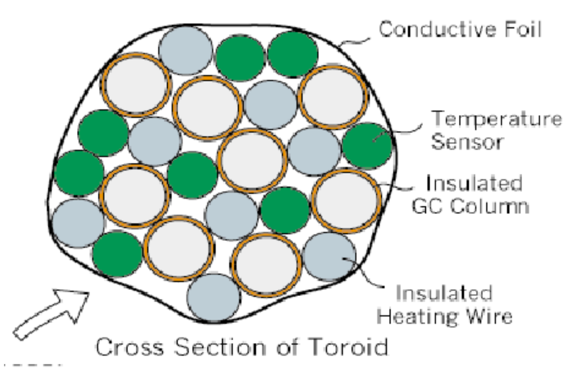
Tunstall (Liverpool University) Wein Filter

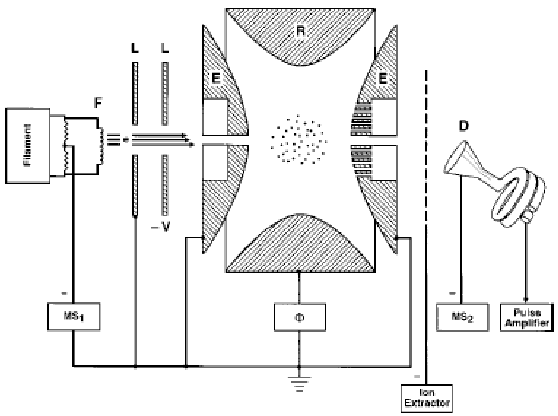
Miniature GC/MS Instruments

	Mass	Power	Volume (Electronics Size)	Sampling (Rate/Methods)	Pumps	MS Type (Resolution\Range \Sensitivity)
JPL GC/MS (Chutjian)	~2 kg	4-6 W	0.003 m^3	Preconcentrator	Ion	Paul trap (1-300 D\ m/Δm = 324\ 500 ppt)
Hapsite (Inficon, Inc.)	16 kg	30W	0.036 m^3	Preconcentrator with internal pump for headspace sampling, standard injection	Getter	Quad (1-300 D)
Huygens GCMS	17.3kg	71W peak, 41W average	0.014 m^3	Direct atmos. sampling, batch GC, pyrolysis	Sputter ion pumps, getters	Quad (2-141 D)

Recommendations -- 2010

- A standard GC column with integrated heating (Waite) interfaced to miniaturized ion trap (Chutjian)
  - Power 5 W
  - Volume 3000 cm^3
  - Weight 2 kg
- Capable of a full GC analysis every 10 minutes, 1-300 m/z range, isotopic resolution





Recommendations -- 2020

- An integrated micromachined GC/MS, based on Sandia μChemlab & micromachined quad array or Wein filter
- Same analytical capabilities as 2010 recommendation
  - Power 2.5 W
  - Volume 1500 cm^3
  - Weight 1 kg